LCA for Food Products (Subject Editor: Niels Jungbluth)

Literature Review

LCA Studies of Food Products as Background for Environmental Product Declarations*

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Abstract

Goal, Scope and Background. Food production systems invariably precipitate negative environmental impacts. Life cycle assessment (LCA), a standardised tool for evaluating the environmental costs of manufactured goods, is currently being expanded to address diverse product groups and production processes. Among these is food production, where the technosphere is tightly interlinked with the biosphere. The goal of this paper is to contribute to exploring the suitable functional units, system boundaries and allocation procedures for LCA in food production in general, and the product category rules (PCR) and environmental product declaration (EPD) for food products in specific.

Main Features. A review of published scientific articles and conference papers treating LCA of food products is used to highlight and discuss different ways of defining the goal and scope of the LCA of food products, with an emphasis on defining the functional unit, setting the system boundaries and choosing a co-product allocation method.

Results. Different ways of choosing the production system and system boundaries, functional unit and co-product allocation procedure are shown and discussed. The most commonly used functional unit is based on mass, but there are more sophisticated ways of expressing the functional unit for food products, like protein and energy content. A quality corrected functional unit (QCFU) is proposed.

Discussion. Choice of the functional unit is highly dependent on the aim of the study. Mass or volume may be more relevant, as a basis for the functional unit, than land use. However, other qualities of the food product like nutrient content, like energy content, fat content, protein content or a combination thereof, would be a more sophisticated functional unit for food products.

Conclusions and Recommendations. While LCA methodology is a valuable tool in conducting environmental impact assessments of food products, further methodological development to account for food-specific functions, like nutrient content, is needed. To facilitate a valid comparison between different products, system boundary description and functional units need further development and standardisation. A more sophisticated choice of a functional unit, taking nutrient content of the food into consideration in addition to mass, could both reflect the function of the food better and provide a solution to the co-product allocation problem that exists for some food products.

Keywords: Agriculture; environmental product declarations (EPD); fishing; food; functional unit; life cycle assessment (LCA); product category rules (PCR)

Introduction

Provision of food satisfies a basic human need. As traditional food production systems have given way to intensive methods in order to meet the growing demand of an increasing population, food production has become an important contributor to the depletion of natural resources, pollution and climate change (Kramer et al. 1999, Nonhebel 2004, Tukker et al. 2005). Food production is much more energy-intensive as a result of industrialization. Human power has been replaced by mechanical power, which has led to an increased use of fossil energy resources. In fisheries, for example, sail boats and row boats have been replaced by mechanically propelled vessels.

Increasingly, inputs to production are imported to the farm for agriculture production (Stern et al. 2005). The off-farm purchase of manure, inorganic fertilizers and feed, results in increased transport and the production of by-products that cannot be used on the farm. Outputs must be transported to market or handled as waste. Production has also shifted from mixed crops to monocultures, which represent a new environmental challenge.

Concerned consumers are calling for changes to address these issues. Policymakers and producers therefore require scientifically defensible information concerning food products and production systems (Ziegler et al. 2003). In recent years, life cycle assessment (LCA) has evolved as an important tool in improving the environmental performance of food production systems. According to ISO14040, LCA can be used in product development and improvement, strategic planning, environmental performance indicator selection and marketing (ISO 14040 2006). Ceuterick et al. (1998) provide an overview of the goal of LCA for food products. These in-

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clude the provision of information, hot-spot identification, short-term system optimising and long-term strategic planning (Ceuterick et al. 1998).

The main phases of an LCA according to ISO14040 are goal and scope definition, inventory analyses, impact assessment and interpretation. Goal and scope definition for LCA includes, but is not limited to, the description of the system to be analysed and a clear definition of the system boundaries, description of the function of the system(s) and the functional unit and allocation procedures (ISO 14040 2006). The end-results of an LCA are dependent on the systems boundaries, the functional unit is the unit to which the results of the LCA are related, and used further for the communication of the LCA-results. The co-product allocation procedures are important for food products, because food production system characteristically produces more than one economic output (Ceuterick et al. 1998, Thrane 2006), and can significantly alter the results.

Environmental product declarations (EPD) address the need for communicating LCA results. The term EPD in this paper is used on environmental product declarations that belong to a type III-programme which requires an LCA according to the ISO14040-standards, an approval of the LCA and a third party verification (ISO 14025 2006). The main features of EPDs are that they shall enable comparisons between products. Module-EPDs can also be added up to an EPD of the whole life cycle of a product. ISO14025 requires that product category rules (PCRs) should be developed. PCR is a set of specific rules, requirement and guidelines for developing the EPD for one or more products that can fulfil equivalent functions – called the product category. A PCR provides information about functional unit, system boundaries, impact categories and data quality and other parameters for the underlying LCA (ISO 14025 2006). Fet and Skaar (2006) describe how to develop the EPD based on PCR in accordance with the ISO 14025-standard with examples from the furniture industry. The information provided in the EPD can also be used when consumer labelling should be decided on minimum or maximum criteria. Within the food sector, PCR and EPD are found in the dairy transport sector (Andersson 2001). PCR for wild caught fish is under development (Schau 2006).

In the preparation of the PCR, ISO 14025 requires that an LCA of the product in question should have been performed (ISO 14025 2006). This paper is based on a review of LCAs for food products.

Defining the functional unit and setting the system boundaries are important for the result of an LCA and crucial when comparing different products. A throughout definition and discussion of both the functional unit and the system boundaries are therefore necessary in any LCA and in an LCA of food products in particular, where the function of the product is different from most other commodity products and the system boundaries to nature could inherently be more complex. Based upon different studies and the definition of the functional units, alternative functional units, the use of system boundaries and allocation are discussed for the purpose of choosing the best alternatives in future development of PCRs for fish products and for the use in related EPDs.

1 Main Features

Eighteen peer-reviewed journal articles describing LCA of one or more food products published in scientific journals between 1998 and May 2006 form the basis for the review (**Table 1**). Each article describes an LCA of one or several food products, food ingredients or food production processes. Articles published after 1998 as a starting point were chosen because the LCANET food, a European wide network of LCA and food experts published their definition document (Ceuterick et al. 1998) in 1998. ISO14040 (ISO 14040 1997) was also a new international standard at that time.

Beverages are not included in this study, as the function or purpose of beverages is considered to be different from food. Nevertheless, there are some overlaps. Talve (2001) defines beer as a food product because the main ingredient in beer is grain. However, beer is not included in the review. Many fruit and vegetables can be used in the production of juice, which have the same or similar nutrient content as that of the fruit or berries themselves, i.e. vitamins. Juices are also considered as beverages and not a part of this study. Milk, however, is an important ingredient in many other food products, i.e. cheese (Berlin 2002) and sauces (Katajajuuri et al. 2004), and therefore included in the review.

The articles selected for the review should as far as possible give a total description of the LCA so that information about the functional unit, system boundaries, allocation procedure, inventory results and impact assessment categories could be

Table 1: Food products/ingredients evaluated using LCA

Food product/ ingredient:		References:
Apples	Braeburn Golden Delicious, Jonagold, Idared, Maigold and others	Milà i Canals et al. (2006) Mouron et al. (2006)
Vegetables		Jungbluth et al. (2000)
Wheat	Winter-wheat	Brentrup, Kusters et al. (2004a, 2004b)
Bread		Andersson & Ohlsson (1999)
Sugar	Sugar beet Cane-sugar	Brentrup et al. (2001) Ramjeawon (2004)
Milk		Hospido et al. (2003) Cederberg & Mattsson (2000) Cederberg & Stadig (2003) Eide (2002) Haas et al. (2001)
Cheese		Berlin (2002)
Meat	 Pig Organic-beef	Jungbluth et al. (2000) Basset-Mens & van der Werf (2005) Cederberg & Stadig (2003)
Shrimp		Mungkung et al. (2006)
Fish	Cod Flatfish Tuna (Skipjack and Yellowfin)	Ziegler et al. (2003) Thrane (2006) Hospido & Tyedmers (2005)

used as a background when developing PCR for food products. The variety in the choice and purpose of the functional units of the articles in Table 1 was not sufficient for a good discussion. Therefore, other articles and conference proceedings from the LCA food network, and other published work on LCA of food (see Table 2), have been considered for exploring the functional unit in more detail.

2 Results and Discussion

2.1 Production system and system boundaries

In LCA, the system boundary should ideally be set where nature ends and the technological system proceeds. The choice of system boundaries, however, is always debatable, particularly with food production, where the inclusion of biological processes renders the distinction between technological systems and nature unclear (Berlin and Uhlin 2004, Berlin 2002). LCA provides a systematic approach to impact analysis and, ideally, should include all phases of the product's life cycle, from raw material extraction to consumption and waste disposal. Only a few of the studies in the review attempted to cover the entire life cycle of a product. Rather, emphasis was given to those aspects of the product life cycle that were deemed most important. **Fig. 1** depicts the general life cycle of most products. For food products, the production phase represents agricultural activity. Most of the studies omitted the consumption and waste handling phases, with the exception of Andersson and Ohlsson (1999), Berlin (2002), Eide (2002), Jungbluth et al. (2000), Thrane (2006) and Ziegler et al. (2003), whose research indicated, in general, that the direct environmental impact of the consumption and waste handling phases were of minor importance relative to the production phase. However, the minimization of product loss in the consumption phase was important because all the environmental impact in the life cycle is related to the product which is actually consumed.

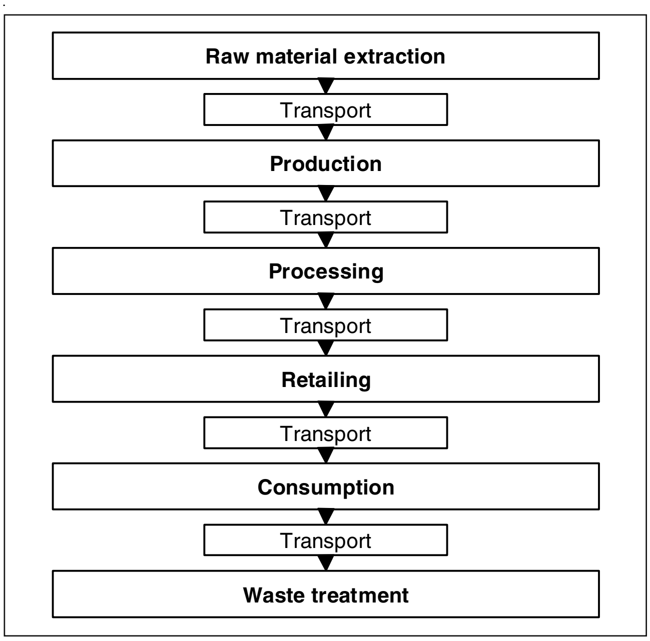

Fig. 1: General life cycle of food products

Equal system boundaries are crucial when comparing different products. There are at least two aspects of system boundaries; 1) where to set the system boundaries between the system under study and other man-made systems, and 2) where to set the system boundaries between the technosphere and nature. The latter aspect is of especial interest for the LCA of food products, because the life cycle of food products is tightly interlinked with nature, both at the beginning of the life cycle and in the consumption phase: Does the human body belong to the technosphere or nature? The boundaries between technosphere and nature are also of interest at the beginning of the food life cycle: Ellingsen and Aanondsen (2006) compare wild caught cod, farmed salmon and chicken. Based upon their analysis, it can be discussed whether the feed of the cod should be included in the analysis when the use of biomass (fish) in the feed for salmon and chicken is included in the analysis. An argument against including the feed (fish) of the wild caught cod is that this is part of nature (and not of the technosphere), while the feed (i.e. fish) to the salmon and chicken has entered the technosphere and should, as such, be included in the LCA.

2.2 Defining the functional unit

The functional unit is the reference unit that forms the basis for comparisons between different systems. The functional unit must be defined in the goal and scope definition phase of an LCA.

In most of the articles investigated (see Table 1) the functional unit was based on mass (i.e. 1 kg or 1 metric tonne) alone. The second most frequently used functional unit was based on volume. Hospido et al. (2003) and Eide (2002) used volume to define the functional unit for milk production. However, other ways of defining the functional unit are presented in various publications and are described below.

A more sophisticated way of defining the functional unit is to include quality aspects (in a wide sense in the meaning of the quality) in the definition. The quality of a food product can be described by the texture, viscosity, the availability to keep the quality or represented by the nutrient content of the product. The nutrient content is described by a range of factors like the amount of carbohydrate, fibre, vitamins, minerals, essential amino acids, energy, fat and protein or total dry substance in the product. Marshall (2001) used the nutrient content as the functional unit in three different ways; 1) Amount to provide 1 kilogram of a nutrient; 2) Amount to provide the daily recommended dietary intake (RDI) for a nutrient; 3) Amount to provide the summation of the amounts that provide the daily RDI for each nutrient. The relative impact of frozen peas and spinach depended on the choice of the functional unit (Marshall 2001).

The functional unit could also be based on energy content of the food. However, this is absent in the revised articles and also rare in other LCAs of food products. Even if the functional unit in the study of Grönroos et al. (2001) are 1,000 litres of milk and 1,000 kg of rye bread, they do a comparison between milk and rye bread based on the energy content in the two different food products. This shows that energy content is used to compare the function of a

Table 2a: Functional units that include other aspects than simple mass or volume

Functional unit based on:	Apples (Mouron et al. 2006)	Conventional and organic milk (Cederberg & Mattsson 2000)	Organic milk (Cederberg & Stadig 2003)	Intensive, extensified and organic milk (Haas et al. 2001)	Pig (Basset-Mens and van der Werf 2005)	Shrimp (Mungkung et al. 2006)	Cod (Ziegler et al. 2003)	Cod, salmon and chicken (Ellingsen & Aanondsen 2006)	Various food products (Dutihl & Kramer 2000)	Wheat for bread baking (Audsley 2003)	Wheat for bread baking (Charles et al. 1998)
Mass or volume of product					1 kg						1 t
Typical portion or packaging size						3 kg	400 g	200 g			
Economic value	1 rcpt [a]										
Emotional value									1 Dfl [d]		
Energy, fat or protein content or combination thereof together with quantity		1,000 kg ECM [b]	1 kg ECM [b]							1 t 12% protein-corrected	1 t 13% protein-corrected
Land use	1 ha			1 ha	1 ha						1 ha
Production unit				1 unit [c]							

[a] total receipt of the farm recorded in Swiss franc (CHF)
[b] energy-corrected milk
[c] for the biodiversity, landscape image and animal husbandry impact categories
[d] Dutch florin

Table 2b: Different functional units investigated by Marshall (2001)

Functional unit based on:	Peas [g]	Spinach [g]
Quality or nutrient content and combination thereof (amount to provide):		
1 kg carbohydrate	1.03E+04	2.00E+05
1 kg fibre	2.38E+04	3.23E+04
1 kg folates	2.13E+09	1.11E+09
1 kg vitamin C	8.33E+06	1.67E+07
RDI for carbohydrate (300 g)	3.09E+03	6.00E+04
RDI for fibre (25 g)	5.95E+02	8.06E+02
RDI for folates (0.0004 g)	8.51E+02	4.44E+02
RDI for vitamin C (0.06 g)	5.00E+02	1.00E+03

product. Ellingsen and Aanondsen (2006) use 200 g fillet as the functional unit, as this is the meat content (and hence main protein source) in a standard dinner meal served at a restaurant for cod, salmon or chicken. Martin and Seeland (1999) related the emission of nitrogen (N), phosphorus (P) and methane (CH_4) to the protein output for human consumption from milk and beef production systems. Also the protein content of milk is a relevant aspect to consider for the functional unit, as this influences the yield of cheese (Berlin 2002). In the case study performed by Audsley (2003), the functional unit is '1 tonne of 12% protein-corrected wheat for bread making' (Audsley 2003), or that quantity of wheat containing 120 kg protein. The total protein content of the wheat can be used to describe the quality. For milk, a functional unit that takes both the fat and the protein content of the milk into consideration, in addition to the quantum (mass), is the energy corrected milk (ECM), that is used by the dairy industry (Cederberg and Mattsson 2000). Köllner (2003) mentions the possibility of basing the functional unit on biodiversity, although a functional unit based on mass was used. The reader should be aware of that land use, in addition to serving as a basis for the functional unit, also is increasingly used as an impact category in many studies. The development of a land use impact category is described in (Lindeijer 2000, Lindeijer et al. 2002, Milà i Canals et al. 2007, Udo de Haes 2006).

LCA from various sources that used functional unit(s) other than mass or volume are shown in **Table 2a** and **b**. Table 2a gives an overview of some common functional units used in full LCAs. Dutilh and Kramer (2000) use the emotional value of food products for the functional unit, whereas Mouron et al. (2006) and Haas et al. (2001) use one recipient and a production unit, respectively, in addition to area of land used as a basis for the functional unit. In Table 2b, different functional units used by Marshall (2001) are presented in a study to investigate how alternative functional unit affects the results.

The primary function of food is to satisfy the human body's need for nutrition. Food also has other functions, e.g. to provide energy and nutrients for the body, to give the good feeling from a delicious looking meal, to keep a good quality over time. The functional unit can reflect one or several of these aspects. The most common functional unit is based on quantity (measured in kg or litre) of the food product. As seen from Table 2 other functional units are also used for food products. The idea is to find a common unit that the environmental impact of the products can be evaluated against.

However, in some of the studies, the choice of a functional unit is not clearly justified and there is no clear distinction between the functional unit and the reference flow[1]. If the reference flow is the quantity (e.g. measured in kg), it does not necessarily reflect the function of the product properly.

[1] The reference flow is a measure of the output from processes in the system under study required to fulfil the function of the system ISO 14044 2006: Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006), ISO, Geneva. If the function of a food production system is to deliver 120 kg protein, the reference flow in a system that is producing wheat with 12% protein content would be 1 tonne, but the reference flow in a system with 15% protein content-wheat would be 0.8 tonne.

By making clear divisions between the functional unit and the reference flow, the functional unit can be chosen more sophisticatedly and reflect other functions of the product, e.g. the quality. Nutrient content is a quality aspect of food products that separate food from other commodity products, and provides an opportunity to be used as basis for the functional unit in an LCA of food products.

The most common, one-dimensional functional units are based on mass or volume. The mass or volume is a simple measurement of the quantity of the product and often used to quantify the price of the product. The annual consumption or typical portion or packaging size which could be based on mass or volume is relatively easy to understand, but would vary among different products and persons. "As meals may strongly vary from day to day, the most appropriate functional unit for food may be a one-year consumption. That choice would, however, leave very little scope for identification of improvement options for individual components" (Dutilh and Kramer 2000). However, because there can be a negative relation between yield and quality for wheat production (Charles et al. 1998) and there is reason to think this could apply for other food production as well, taking only the quantity into consideration for the functional unit may mislead the purchasers of food products. When the functional unit is based on mass or volume, the water content of the product can be crucial. Water may add both mass and volume to a food product while other functions or quality aspects, like nutrient contents, i.e. energy and protein content, of the food product remain the same or similar. How much water is included is a relevant question if the functional unit is based on mass or volume of the product. Using the total dry substance as a basis for the functional unit could be used to compare same products with different preservation techniques being used (i.e. dried or fresh). Using mass or volume as the basis for the functional unit is straightforward and easy to understand, but ignores an important function of food products.

Using the economic value as a basis for the functional unit would allow comparisons between ranges of different products. However, because price differences for products with the same function may lead to direct and indirect rebound effects[2], using only economic value as the functional unit may not be sufficient for a buying decision.

If economic values are related to the environmental impact, a measure of the eco-efficiency can be obtained. Eco-efficiency is a measure of value performance compared with the related environmental impacts (Fet 2003). The economic value is also based upon a range of other factors (like energy, resources, work and transport). The emotional value of a product is reflected in the price; exclusive brands and prepared meals can be priced higher than other products with the same nutrient content. The emotional component is independent of the nutritional component and the energy requirement (Dutilh and Kramer 2000). Using the emotional value as the functional unit is related to the functional unit based on economic value. Dutilh and Kramer (2000) indeed relate the energy use to a monetary unit, Dutch florin (Dfl).

Basing the functional unit on the quality, like the ability to keep fresh, may be complicated, as at least some of the quality aspects depend on the storage conditions, on time and on preparation mode. The nutritional values of some nutrients depend on the choice of complimentary foods (Andersson et al. 1994).

Functional units based on the energy content of the food alone is rare in the articles revised. This is strange, since one of the functions of food is to deliver energy to the body. Energy content of food should be well recognised for the consumers. However, energy content is often presented together with the content of fat and protein, as shown in Table 2. One possible explanation why energy content alone is rarely used as a functional unit in LCA may be that the fat content which influences the energy content varies considerably for some food products between different locations and seasons. This is the case for food products like many fish species. In Atlantic herring (*Clupea harengus*), for example, the fat content varies between 1–17%. The fat content of the herring caught in the North-Sea is 5% in March and April but 15% in September and November (Austreng 1986). Such variations make energy content as a functional unit more complex to use than mass, but it is not impossible to account for.

The energy-corrected milk (ECM) unit, see Table 2, includes multiple functions (i.e. total mass, fat content and protein content). The fat-corrected milk (FCM) is a similar approach taking the fat and the quantity of milk into consideration. FCM and ECM are calculated quite easily when the quantity of milk, fat and, for ECM, protein content are known[3].

The protein content of the food is also a main physical function of food. The protein content of milk, for example, depends on breed of cattle and fodder used. The choice of fodder will affect the environmental impact of the system (Berlin 2002); therefore, using protein content as a functional unit could provide an interesting insight and results. Using the quantity of wheat containing 120 kg protein (see Table 2) or "1 tonne of 12% protein-corrected wheat for bread making" (Audsley 2003) as the functional unit is a way of tak-

[2] The rebound effects means that when the price of a product decreases, the purchaser can afford to buy more of the same product (direct rebound effects) or buy more of other products and services (indirect rebound effects), which will, ceteris paribus, increase the environmental impact. Binswanger M (2001): Technological progress and sustainable development: What about the rebound effect? Ecological Economics 36, 119–132; de Haan P, Mueller MG, Peters A (2006): Does the hybrid Toyota Prius lead to rebound effects? Analysis of size and number of cars previously owned by Swiss Prius buyers. Ecological Economics 58, 592–605; Hertwich EG (2005): Consumption and the Rebound Effect: An Industrial Ecology Perspective. Journal of Industrial Ecology 9, 85–98

[3] If the lactose content of the milk is also taken into account, the formula for ECM looks like this: ECM = milk yield (kg) x (38.3 x milk fat (g/kg) + 24.2 x milk protein (g/kg) + 16.54 x milk lactose (g/kg) + 20.7)/3140. Here, taken from Kokkonen T, Taponen J, Anttila T, Syrjala-Qvist L, Delavaud C, Chilliard Y, Tuori M, Tesfa AT (2005): Effect of Body Fatness and Glucogenic Supplement on Lipid and Protein Mobilization and Plasma Leptin in Dairy Cows. J Dairy Sci 88, 1127–1141, which cited Sjaunja L-O, Baevre L, Junkkarinen L, Pedersen J, Setälä J (1990): A nordic proposal for an energy corrected milk (ECM) formula. In: Gaillon P, Chabert Y (eds), Twenty-seventh session of the International Committee of Recording and Productivity of Milk Animals, July 2–6, 1990, Paris, France, pp 156–157

ing the protein content of wheat into consideration, as this is an important quality indicator. The method of using correction factors is also used for oilseed crops and sugar beet crops (Audsley 2003).

Area of land used reflects an effort to incorporate non-market goods such as environmental services in the LCA framework, and raises interesting questions regarding the influence of land use practices on the outcome of such an assessment. Berlin and Uhlin (2004) and Grönroos et al. (2001) argue that land use should be considered as the basis for the functional unit for agricultural products because this would facilitate policy decisions regarding land use and regional planning. Basing the functional unit on land use, however, precludes the inclusion of the land use impact category which would complicate LCAs where the entire value chain, not only agriculture, is included.

Brentrup (2003) suggests using a product-related functional unit (i.e. based on mass) rather than an area- related functional unit in order to be capable of assessing differences in land use efficiency. An LCA where the functional unit is based on land use will bring the LCA method closer to the Environmental Impact Assessment process, aims of which are, among other, to assess location choices (Tukker 2000). This also shows that the choice of the functional unit is highly dependent on the aim of the study. For example, in studies intended to advise consumers regarding food products (Jungbluth et al. 2000), mass, volume or nutrient contents may be more relevant than land use as a basis for the functional unit.

2.3 Co-product allocation procedures

When one process results in two or more valuable product outputs (co-products), allocation of emissions and resources used in the production of the products should be done. Co-production is a common issue in food LCA because food production is often characterized by closely interlinked subsystems (Cederberg and Stadig 2003, Ceuterick et al. 1998, Thrane 2006). For example, in the production of milk and beef, Cederberg and Stadig (2003) state: "The two production schemes are closely interlinked; surplus calves and meat from culled dairy cows are an important base for beef production" (Cederberg and Stadig 2003, p. 350). ISO14044 (2006) suggests, for processes resulting in more than one economic output, that the assessment should primarily avoid allocation by separating multifunctional processes into sub-processes or through system expansion; secondarily, allocation should be performed according to physical relationships between the environmental burdens and the functions; and thirdly, impacts can be allocated according to another relationship (i.e. economic) between environmental burdens and functions.

Cederberg and Stadig (2003) perform a system expansion of a milk- and beef-production system and compare the result to economic allocation. In the system expansion, the core system of combined milk and meat production is expanded by an alternative production of meat through suckling cows which deliver meat and calves for meat production, but no milk. By subtracting the result from the meat only-production LCA from that of the combined milk and beef-production LCA, the environmental impact of milk alone can be found. Cederberg and Stadig (2003) conclude that system expansion should be preferred over economic allocation to obtain the most reliable results. Also Thrane (2006) uses system expansion for the fish catch operation and processing stage, while allocation based on mass, volume or economic value are applied on the other stage of the life cycle of the fish product. In an attempt to compare system expansion with economic allocation and mass allocation in the fish catch operation, Thrane found that the relative fuel consumption (litre fuel per kg fish) is significantly influenced by the allocation procedure chosen for all 9 species investigated. For mussels, herring, mackerel and sand eel, the allocation method is determined for the results (Thrane 2006).

Cederberg and Mattsson (2000) use the causality between the amount and quality of the feed and the output milk and meat, in addition to allocation based on economic value and mass. Another, but similar, biological causality is the demand for fodder needed for lactation, body maintenance and recruiting of cows' calves, used to allocate between milk and meat (Eide 2002). This hypothetical example illustrates the use of biological causality: A cow produces 5,000 litres of milk and 600 kg meat with food composition type A and emits 50 kg methane. If we want to increase milk production by one litre and keep the meat production constant, this can be done by changing the food composition slightly to food type B, but the methane emissions increase by 0.005 kg. This information can be used to allocate the methane emissions on the milk: 0.005 kg methane per kg milk allocates 25 kg of methane to the milk and the remaining 25 kg of methane to the meat.

Economic allocation was most commonly employed in the food product studies revised, although in a few cases, mass allocation was used. Another basis for co-product allocation was permitted emission of pollutant (Eide 2002) and volume for storage at home (Ziegler and Hansson 2003).

Subdividing the unit process is a way to overcome the allocation problem, although this requires more detailed information of the processes, but should be obtained when such information is available at a reasonable cost. It can be discussed whether using a biological causality for fodder demand and the production of milk, calves and meat, as Cederberg and Mattsson (2000) do, is a way to sub-divide a unit process or uses a biological causality. Ekvall and Finnveden (2001) argue that to be able to sub-divide a process, it should be separated in space or time. This is not the case for milk and beef production in a cow. To solve the allocation problem by subdividing has been shown to be very rare (Ekvall and Finnveden 2001).

The authors that use system expansion argue that their results are more reliable than results obtained by using another co-product allocation procedure. However, the method of system expansion is more complex, and needs more data from other systems. If system expansion is applied without substituting the additional function, the functional unit will encompass more than intended, which makes it very difficult to use when the product should be assigned in a prod-

uct category. For example, in a milk production system that also produces beef, system expansion without substituting would lead to a system with a function of delivering both milk and beef. This product mix could belong to the product category food, but not to milk or meat. A production system producing wheat, but also straw as a by-product, could not belong to the product category wheat or food if the system is expanded to include the straw in the functional unit. However, system expansion with subtracting of the additional function or the so-called avoided burden approach could solve this problem as shown by (Thrane 2006).

Biological causality is not mentioned in the ISO14044 standard step 2 for handling co-product allocation, where only physical causality is mentioned. However, when it comes to food production, biological causality should be equal to physical causality, as long as the different products and functions "reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system" (ISO 14044 2006). The amount of the important greenhouse gas methane (output), for example, can be reduced by changes in the fodder composition (input) for cows (Giger-Reverdin et al. 2003, Ward et al. 1993), which is important for the quantity and quality of milk and meet (products or functions) the system delivers (Berlin 2002, Cederberg and Mattsson 2000) . As most food production includes biological processes, allocation according to biological causalities is an opportunity.

Economic co-product allocation is that which is used most, and is motivated by the fact that the economic value of the product is the driving force of the producer (Ziegler and Hansson 2003), and is often the easiest way to perform the allocation if economic data are easily obtained. Economic value is also mentioned as a basis for allocation as an example in ISO 14044, although ISO 14044 also states that: "The inventory is based on material balances between input and output. Allocation procedure should therefore approximate as much as possible such fundamental input/output relationship and characteristics" (ISO 14044 2006). So, when most studies argue that mass or volume is a very relevant measure of the system's performance, by choosing a functional unit related to mass or volume, why are not mass or volume also relevant for choosing the basis for allocation? Important to note in this respect is that using economic allocation when the functional unit is based on mass or volume would give the same result as to use a functional unit based on economic value together with an allocation based on mass or volume.

Prices, which are involved in economic allocation, include different costs, also some environmental costs - but not all. Prices are also sensitive to subsidies, which are common in food production systems (FAO Media Office 2003, Schrank 2003). Therefore, there may be an information loss or double counting when the economic value is used as the basis for the allocation.

Mass, volume or quality of the product (i.e. nutrient content) as described in the results and discussion of the functional unit, could be used as a basis for the allocation of food products. Choosing a thought-through and sophisticated functional unit could help solve the co-product allocation problem for some cases in food product LCA. For example, in fisheries catching different species, the fuel needs to be allocated between different species (Thrane 2006). If the functional unit is the energy content in the fish delivered, there is no need to allocate between the different fish species. Similarly, if the functional unit is a given quantity of species x, then the energy content can be used to allocate fuel on the different species as proposed by (Ayer et al. 2007), or by the protein content or by both. By applying the quality corrected functional unit (QCFU) as described in formula (1), the co-product allocation problem may be overcome for some food products or, if another functional unit is chosen, the result of formula (1) could be used as a basis for co-product allocation.

3 Recommendations for PCR and EPDs

3.1 System boundaries

The definition of system boundaries could determine the outcome of an LCA. The products in the revised papers have different system boundaries, such that a comparison between different studies is difficult. The different system boundaries clearly demonstrate the need for a set of rules to determine the system boundaries for different product categories so that a comparison of the environmental impacts of different units of products can be possible. Recommendations on how to set the system boundaries can be made available through PCRs for different food products.

3.2 Functional unit

The review has shown that the most common functional unit is based on mass or volume. Other bases for functional units identified in this paper are quality aspects, energy or protein content, value, one recipient, production unit or area of land used. Also combinations thereof are in use.

Christiansen et al. (2006) suggest comparing the environmental impact of "the same amount of money spent" to an average product from the same product category and an average consumer product in EPD aiming at consumers. This is comparable to use economic value as a functional unit.

Comparability is critical for EPDs. To be fully comparable according to ISO14025, the products need to be based on the same PCR. (ISO 14025 2006)

A functional unit representing multiple functions can be realised analogous to the procedures of allocation with use of system expansion (Charles et al. 1998). However, the protein content of the wheat can be influenced by applying different amounts of nitrogen fertilisation in the agricultural phase or mixing different wheat varieties. How to realise a multiple aspect functional unit when the quality parameter cannot be influenced, however, will need to be analysed further. An approach similar to the ECM-calculations could be used for other products, like fish products, for instance. The calculations of the quality corrected functional unit (QCFU) must consider the quantity, the fat content, the protein content and the carbohydrate content in a similar way as that for ECM.

A general formula for QCFU:

$$QCFU = \text{yield [kg]} \cdot (X \cdot \text{fat [g/kg]} + Y \cdot \text{protein [g/kg]} + Z \cdot \text{carbohydrate [g/kg]} + k) \quad (1)$$

X, Y and Z are factors and k is a constant which should be agreed upon among experts on different food products. Other factors could be added to the equation to account for other quality functions of food, like vitamin or omega-3 content.

The analysis has shown that a discussion about the choice of functional unit is an essential part of an LCA of food products. The choice of functional unit in the underlying LCAs is further closely linked to the definition of a product category. The analysis has shown that there are already different ways of defining the functional units of food products, and the challenge is to define these in a common way for different product categories. Since the function of food is much more than just to fulfil the need for a full stomach (e.g. fill it with a quantity of mass), the way of presenting nutrient content, other quality aspects and economic value in the functional unit of food products has to be addressed in the development of PCRs.

To summarise this discussion: The functional unit should be kept simple, but as long as the reference flow in the LCA takes care of the simplicity of the calculation, the functional unit could very well be based on other parameters than mass or volume. Because there can be a negative relation between yield and quality, the functional unit should take the quality into account. This can be done by applying correction factors (e.g. for fat and protein), such that the functional unit still can be easily understood. A QCFU as proposed in this paper would take the following two issues into consideration: 1) A functional unit based on mass is most commonly applied as a basis for the functional unit in LCA of food products, and 2) Nutrient content is an important quality aspect of food products.

3.3 Co-product allocation issues

The co-product allocation issue is important because it strongly influences the result of an LCA. Here, we discuss a systematic way of handling the co-product allocation issues as described in the ISO14044-standard and how to handle co-product allocation in EPD and PCR for food products.

One of the main uses of LCA and certainly an important goal of EPD is to overcome the deficit of the economic system to provide the total cost (environmental cost inclusive) of a product. Besides the price of a product, LCA and EPD are aiming at giving additional information to the decision maker. Using economic allocation could introduce this deficit of the economic system into LCA and EPD.

The analysis has shown that the PCR has to establish the allocation procedure and that this must been seen in relation to the choice of functional unit. Some functional unit could in some cases eliminate the co-product allocation problem. Remaining co-product allocation problems should be solved according to the priorities in ISO14044, taking into account the following remarks: System expansion should only be used where there is a possibility to subtract the additional function. In food production, biological causality should be put on a par with physical causality. If there is still a co-product allocation problem to solve, mass or volume and different quality aspects, including nutrient contents of food should be regarded alone or in combination as a basis for food products. The result of the QCFU as presented in formula (1) could be used as a basis for co-product allocation. Economic co-product allocation should be used with care in LCA of food products aiming at EPD.

4 Conclusions

This paper has revised papers that present LCA-studies of different food products. The review shows that the choices of system boundaries, the definition of functional unit and allocation procedures play an important role in the LCA of food products. However, the review also shows that several methods are used, and it is not obvious how to compare products against each other.

Food product systems closely interlink nature and the technical sphere. Since the choice of system boundaries strongly influences the results, there is a need for a set of rules to determine the system boundaries such that comparison of the environmental impacts of products can be possible. How can PCR help to do this? Recommendations on how to set the system boundaries can be made available through PCRs for different product categories. The choice of functional unit in the underlying LCAs is closely linked to the definition of a product category. Further, system boundaries descriptions in the PCR should provide opportunities to include the whole life cycle, but also part of the life cycle, so called modules. The system boundaries used in the LCA and the resulting EPD should be clearly described, generally with a diagram showing which parts of the life cycle that are included in the analyses.

A discussion about the choice of a functional unit is an essential part of an LCA of food products. Traditionally, the use of mass or volume has been used as functional units. However, as the analysis has shown, there are several other ways of determining the functional unit depending on the interest of the end-user of the information. Since the function of food is more than just to fulfil the need for a full stomach (e.g. to fill it with a quantity of mass), the way of presenting nutrient content, other quality aspects and economic value in the functional unit of food product LCA should be addressed. A quality corrected functional unit (QCFU) that takes the nutrient content of the food products into account, in addition to the mass, has been presented in this paper. Such a QCFU is currently used for milk products. Further research is needed to define QCFU for other food products.

The choice of the co-product allocation method must be seen in relation to the choice of the other two issues. Choosing a thought-through and sophisticated functional unit could help solve the co-product allocation problem for some cases in food product LCA. By applying a QCFU, the co-product allocation problem may be overcome for some food products or the result of the QCFU could be used as a basis for co-product allocation.

The review of the papers, and the discussion of the functional unit, system boundaries and co-product allocation procedures as they are used in the different studies presented in the papers, show that the functional unit, the system boundaries and allocation procedures are closely interlinked. There are no commonly accepted rules on how to define these three LCA-issues for food, and especially not for fish food. This means that comparing results of different LCAs is very difficult. On the same time, there is a need in the marked to have the possibility to compare food products against each other. To be able to do this, there is a need to develop a set of common rules for how to define the functional unit, how to set and describe the system boundaries and, further, how to handle the co-product allocation procedures. Further, the LCA-information must be presented in a standardised way for each product category. According to ISO14025, this description shall be given in a product category rule. The PCR must include a clear statement on how to define the functional unit, how to set the system boundaries and which allocation rules are to be used in the LCA. The PCR should also include a statement on what the EPD for the product category should look like and which and how the LCA information should be presented. For the fish-food producing industry, the PCR and the EPD will be helpful tools to meet the growing demand for documentation, traceability and information. Establishing PCR that can be used on fish products are under development. Wild fish products are special in an LCA contest as they originate from the wild. Most other food products are farmed, which gives more similarities to the origin of LCA – industrial production, than wild caught fish. This gives rise to several challenges if wild caught fish is to be compared to other food products – some are system boundaries, functional unit, and allocation procedures which have been addressed in this paper. Other challenges relevant for EPD of wild caught fish are which environmental impact categories to use and the traceability of the fish products from sea to table. These challenges are now addressed by the authors.

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